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NUCLEAR POWER IN LESS DEVELOPED AREAS

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by

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INTRODUCTION

1. Among the energy resources of the world, the most novel is the nuclear fuel uranium. It represents energy in a more highly concentrated form than has ever been known before. If it could be economically utilised it would be the cheapest, most easily transported fuel in the world. It is obviously of special interest to the less developed areas of the world where distances are often great, transport facilities limited and where cheap sources of power are urgently needed to raise the standard of living.

2. But to be of practical interest the methods of application of nuclear power must be well proven and commercially viable in the environment of such countries. This paper reviews the general position of nuclear power today. It describes the types of reactor that have been commercially proven and discusses the economic, financial and organisational implications in applying these to less developed areas.

3. In each country there are experts fully aware of the special problems of power generation and transmission as applied to their own environment. No attempt is made to consider in detail what this environment may be or how it varies from one country to another. It is hoped that from the discussions in this paper, the countries themselves will be able to decide whether nuclear power today may usefully contribute to their energy needs.

THE OPERATIONAL STATUS OF NUCLEAR POWER

4. Only two types of nuclear power reactor are sufficiently proven to justify commercial application now. One is the natural uranium fuelled, gas cooled, graphite moderated type "GCR" often called the "magnox" reactor, a reference to its fuel element cladding metal. The other type is the enriched uranium fuelled, light water moderated and cooled system developed in the United States of America.

It has two variants:-

(a) The "BWR" in which the moderator/coolant is allowed to boil and the steam taken to the turbines direct.

(b) The "PWR" in which it is pressurised to inhibit boiling in the primary circuit which includes a heat exchanger, to produce steam for the turbines.

5. Fig. I shows the stations in operation or under construction.[1,2] The GCR range from 30 MWE to 375 MWE output. The Calder Hall and Chapel Cross stations have been running very satisfactorily and it has been found possible to increase output from the original 37 MWE per reactor to 45 MWE. From first commissioning up to March 1962, the eight reactors in these two stations generated a total of over six thousand million KWH, earning for the United Kingdom Atomic Energy Authority a revenue of £6,000,000 from the electricity authorities in the financial year 1961/62.

6. The BWR and PWR range from 15 MWE up to 313 MWE. Of these the three plants at Shippingport, Dresden and Rowe ("Yankee") in the U.S.A., totalling over 400 MWE, have been in operation for some time; in the case of Shippingport since December 1957.

7. There are other types of reactor under construction or in operation in various parts of the world. Although some look quite promising they are not yet proven and could not be considered for commercial application in the less developed areas of the world.

8. Development of a new reactor system is a long and very costly business, so costly that only the most highly industrialised nations have undertaken it. From initial conception of a new system to entry of the first commercial station into service takes about 15 years. The less developed countries will, therefore, inevitably depend on reactor types already developed by the industrialised nations.

9. Their electricity networks are relatively small and could not accept base load units greater than 100-150 MWE. They are therefore interested in smaller units.

10. The essential difference between the GCR, BWR and PWR lies in the type of fuel. The graphite moderated type runs on natural uranium in the form of metal bars canned in magnesium alloy. Production of the metal from ore concentrate and fabrication into complete canned fuel elements involves plant of quite reasonable cost and such plants already exist in a number of the more highly industrialised countries. There is, therefore, a number of alternative potential sources of supply for natural uranium fuel elements. Perhaps the most interesting point is that any country with indigenous deposits of uranium can set up its own ore processing and fuel element fabrication plant at a cost which would not necessarily be prohibitive even for a less developed country.[3] The standards of workmanship involved are rather similar to those in light precision engineering and do not require a background of heavy industrialisation.

11. Light water moderated reactor fuel elements comprise uranium enriched in the U235 isotope to 3 or 4 times natural concentration, in the form of uranium oxide powder compressed into pellets and canned either in Zircaloy, an alloy of zirconium, or stainless steel. Enrichment is carried out in diffusion plants which are very costly and so far have only been built in the first instance to meet a military requirement. Only three countries have such plants in operation, U.S.A., U.S.S.R. and U.K. France has one under construction. Due to its military application highly enriched uranium is very closely controlled and is

not freely available. Reactors using enriched uranium, therefore, have a limited number of sources for fuel.

THE COST OF ELECTRICITY FROM NUCLEAR POWER

12. The economic characteristics of the two proven reactor systems will now be considered and compared with those of conventional types of plant. To simplify the comparisons BWR will be assumed representative of the light water moderated system.

(a) Capital charges - the GCR

13. In the gas cooled reactor using natural uranium the physical size of the reactor unit and therefore to a large degree its capital cost, is governed by the size of the uranium/graphite core assembly. There is a minimum size corresponding to a cylindrical core about 20 ft. in diameter by 27 ft. high containing approximately 30 tonnes of uranium, below which a chain reaction cannot be sustained. To allow continuous power production at any level to take place even this minimum size must be substantially increased. When it is considered that the core assembly must be contained within a pressure vessel and concrete biological shield many feet thick, it will be appreciated that the minimum size represents a substantial and irreducible fixed component of capital cost. In terms of specific capital cost it represents a significant proportion of the cost as unit size falls below about 100 MWE.

14. As shown in Fig. II at 100 MWE the cost of a GCR single reactor station would be about £170/KW and at 150 MWE about £135/KW whereas the 2 x 275 MWE units being built in the United Kingdom cost about £100/KW. This reduction in cost is due to two factors which can be deduced from Fig. III viz. increase in unit size or "scale effect" and increased performance due to intensive technical development.[4]

15. The GCR nuclear power station with construction costs lying in the range £100 to £170/KW is a high capital cost plant. But it is no higher than some hydro electric stations.

16. Assuming that sufficient capital is readily available on normal terms the chief significance of construction cost is the rate at which it is converted to capital charges per KWH sent out. For a given construction cost and loan interest rate, the capital charges per KWH are fixed by the values of amortisation period and load factor appropriate to the plant over its lifetime.

17. Because commercial operational experience of nuclear power stations is at present strictly limited and the true limit of operational life cannot be demonstrated for some years, an amortisation period of 20 years has arbitrarily been assigned to them, compared with 40 years for hydro electric stations, and 25 to 30 years for conventional thermal plant.

18. Again because there is not enough large scale operational experience nuclear station generating costs are customarily estimated on a basis of 75% availability factor, whereas operational experience now accummulating at Calder Hall, Chapel Cross and the first American stations suggests that reactor reliability would permit operation at load factors greater than 90%, and would reduce capital charges per KWH.

(b) Capital charges - light water reactors

19. The BWR and PWR are physically very much smaller than gas cooled reactors due mainly to their smaller inherent minimum core size. This is typically a cylindrical assembly of fuel approximately 5 ft. in diameter and height, although the exact dimensions depend on the U.235 enrichment level.

20. In the case of the direct cycle BWR the elimination of heat exchangers leads to a compact plant arrangement and reduced capital cost typically from £90 to £100/KW for units in the 100-150 MWE range.

21. It is also possible by using fuel of higher enrichment in U235 to reduce the inherent minimum core size. In practice it does not pay to carry this process very far. Increased enrichment results in increased cost of fuel. Therefore, a point is reached where although plant costs associated with physical size diminish with reduction in core size, both capital investment in the core fuel assembly and fuel consumption costs rise to a level which discounts these savings.

22. In small unit sizes, the direct cycle BWR costs very much less than the GCR due to its inherently small physical size. In the very large unit sizes although the capital cost differential is very considerably reduced, the direct cycle BWR is still cheaper.

23. The amortisation period of the BWR is also assumed to be 20 years, for the same reason as for the GCR.

(c) Fuel investment charges

24. The weight of fuel required for 150 MWE units would be 190 tonnes of natural uranium at about £12,000 - £16,000/te for GCR and 27 tonnes of enriched uranium at £110,000 - £130,000/te for BWR representing an investment of about £2.6M and £3.2M respectively, and leading to a unit charge of 0.055d - 0.065d/KWH for reactors in the 100-150 MWE range.

(d) Fuel consumption charges

25. Corresponding to the fresh fuel prices given above for natural uranium and for enriched fuel indicated above are net "buy back" credits on irradiated fuel of the order of £3,000 - £5,000/te and £8,000 - £10,000/te respectively.

26. The net cost of fuel consumed would therefore be about £10,000/te for metallic natural uranium with a mean irradiation capability of 3,000 MWD/te and £110,000/te for ceramic enriched uranium with an irradiation of 15,000 MWD/te. These figures correspond to a cost of heat in GCR fuel of 10d. per million Btu and in BWR of 22d. per million Btu. The GCR has an overall thermal efficiency of 33% which leads to a fuel consumption cost of 0.1d/KWH and the BWR at 30% leads to 0.24d/KWH.

(e) Operation and maintenance charges

27. Although large scale operational experience with nuclear stations is lacking, experience at Calder Hall and Chapel Cross indicates that the costs per KWH for operation and maintenance are similar to those for conventional thermal stations.

(f) Comparison of nuclear and conventional plant

28. Compared with GCR and BWR stations in the range £135-170/KW and £90-£100/KW respectively the specific capital cost of hydro electric stations varies from about £50/KW to over £200/KW. These stations have two main advantages over nuclear units of the same cost: a long amortisation period, typically 40 years, and no fuel cost.

29. Coal and oil fired stations in the 100-150 MWE range of unit size vary in specific capital cost from about £50 to £60/KW. They are, therefore, of relatively low capital cost, with a fairly long amortisation period of about 30 years and thus have low capital charges per KWH. Fossil fuel costs for major power stations range on a world basis from as low as 7d. per million Btu to as high as 70d. per million Btu corresponding to fuel consumption costs per KWH of 0.066d to 0.66d/KWH at 36% efficiency.

30. Because nuclear and hydro electric plant both tend to be of high capital cost it is important to spread their capital charges per KWH as thinly as possible by operating at the highest possible load factor.

31. In a system containing all the types of plant shown in Fig. IV the plant with lowest fuel consumption cost per KWH would be operated at the highest possible load factor consistent with plant availability.

32. Because it has no fuel cost hydro electric plant with unlimited water supply will come first with the highest "order of merit".

33. GCR with its fuel consumption cost of about 0.1d/KWH will come next followed by BWR in the region of 0.24d/KWH.

34. Finally coal or oil fired plant taking fuel at delivered costs above about 22d. per million Btu will supply the medium and lower load factor requirements of the system. Stations taking fuel at less than this cost would of course compete for order of merit with BWR and possibly even with GCR but such extremely low fossil fuel costs are exceptional.

35. Hydro electric plant with only limited water supply and therefore low availability would share the medium or low load factor demand with the high fuel cost thermal plant.

36. From these considerations it is obvious that wherever high availability hydro electric schemes can be developed at reasonable cost they will be the cheapest method of electricity generation. However in many countries water power potential is either strictly limited, too far from the centres of electricity demand or non-existent and the competition then lies between the two proven types of nuclear station and fossil fuelled plant.

37. In such cases it is obvious that except where fossil fuel costs are exceptionally low the comparison shown in Fig. IV is unfairly biassed against nuclear plant. Both GCR and BWR would claim base load priority, GCR by a particularly substantial margin, from coal or oil fired plants. In most electricity networks fossil fuel costs are high enough to ensure high order of merit for nuclear stations throughout their operational life.

38. It would therefore be more appropriate to compare nuclear plant at 90% load factor with fossil fired plant at 75% or lower. Under these conditions both GCR and BWR generating costs would compete with coal or oil at delivered costs well below 40d. per million Btu.

GENERAL ASPECTS OF INTEREST TO LESS DEVELOPED COUNTRIES

(a) Foreign currency

39. The balance of payments is a major problem in practically every country. In the less developed areas most of the heavy or complex plant must come from overseas and therefore the proportion of foreign currency inherent in each type of plant is an important consideration.[3] But it is even more important to consider the foreign currency component of the fuel cost over the lifetime of the station.

40. A country with indigenous supplies of uranium ore could, by manufacturing its own fuel, employ a GCR at a substantially lower expenditure in foreign exchange over the lifetime of the plant than either a BWR or even a fossil fuelled station importing fuel at as low as 30d/10^6 Btu.

41. The amount of local manufacture and construction depends on the stage of industrialisation reached in the country. It is estimated that the percentage of local participation in less developed countries will be in the range 30 - 50% for the GCR and somewhat less for the BWR.[3]

42. The high proportion of civil engineering work in the GCR particularly in the new designs employing a prestressed reinforced concrete pressure vessel is an advantage as much of the work can be carried out by local labour and materials.

(b) Specialised personnel requirements

43. Before embarking on a nuclear power programme it is considered that a top level team should be formed directly responsible to a Government department.[5] The team should consist of experts of a high level of technical education, experience and judgment representing the medical, physics and engineering fields. They should receive special training in health and safety matters in one of the highly industrialised countries having a large scale nuclear power programme.

44. The main function of the team would be to advise the local authorities in the siting of nuclear stations, drawing up detailed procedures on health and safety matters and taking responsibility for immediate decisions such as the evacuation of significant areas of population in the case of a serious nuclear incident.

45. The team should have at their disposal expert advice on such matters as meteorology, insurance, biology and law.

46. A typical staffing schedule for a 150 MWE GCR nuclear power station calls for staff on the following general scale:[6]

Management and technical	-	26
Clerical and general	-	34
Operation, Maintenance and Health Physics	-	147
TOTAL	-	207

47. Of these men less than three dozen require any kind of nuclear or health physics training, the remainder being of conventional power station personnel grades. Of the former no more than half a dozen of the most senior would need training more advanced than that provided by a small well balanced nuclear research centre.

(c) The role of nuclear research

48. Nuclear physics has benefits other than electricity generation to bring to less developed countries. Besides the practical application of radioactive isotopes to medicine, surgery, agriculture and industry, there is the question of original research in the academic institutes of the country.

49. Much basic and applied research connected with nuclear power involves capital investment in heavy equipment beyond the means of most of the less developed countries. Nevertheless it is desirable for the sake of the future that some of the nations best scientific brains should be exercised and developed in such fields. This could be achieved in the first instance by attachment to major research establishments in the highly industrialised countries. In general less developed countries should find it possible to lay down embryo nuclear research centres as a logical extension of the Physics Department of at least one of their universities with the object of carrying out original work in the less capital intensive fields of research.

50. There is perhaps no general rule except that each country must examine its needs for nuclear techniques and education. The education of large numbers of men to a high academic level carries with it the burden of financing the type of work in which their talents can be fully exercised. If no such provision is made the best academic brains will soon be lost to the country concerned.

CONCLUSIONS

51. Both the natural uranium gas cooled graphite moderated reactor (GCR) and the enriched uranium light water moderated reactor system, in its variants BWR and PWR, are well established in a number of countries both in numbers and unit sizes installed. The experience from the first units of each type already in operation although still limited has been very satisfactory indeed. They can be seriously considered for application to less developed countries.

52. Natural uranium as a fuel is attractive not only because of its exceptionally low fuel consumption cost per KWH but because it is financially and technically possible to contemplate setting up ore processing and fuel element fabrication plants in countries that possess indigenous reserves of uranium. But the capital cost of natural uranium reactors is nigh, particularly so in the relatively small sizes most required in the less developed countries.

53. The BWR in these sizes has a very much lower capital cost. This is due chiefly to its inherently simple nature and also to the use of enriched fuel which makes small core sizes possible. However its fuel investment and consumption costs are appreciably higher. Neither the BWR or PWR can compete with hydro power under base load conditions but in units of 150 MWE it is probable that they can begin to compete with coal and fuel oil delivered at about 40d./M. Btu and upwards.

54. Foreign currency payments are of vital importance to a less developed country. When foreign loans can be arranged covering the plant supplied from overseas and where fuel elements are manufactured from indigenous ore the gas cooled reactor can show, over the lifetime of the plant, a considerable saving compared not only with the BWR but also with conventional plant burning imported fossil fuel at 30d/M. Btu.

55. A government executive committee of highly qualified professional men drawn from medical, physics and engineering fields should be established before a nuclear power programme could be launched.

56. A staff of 200 would be required to run a 150 MWE (GCR) nuclear station. Of these less than 30 would need to have nuclear or health physics training and in only six cases would this have to be highly specialised. The remaining 170 would be drawn from conventional thermal plant operating personnel grades.

57. Much basic and applied nuclear research is too costly for the less developed countries. Embryo nuclear research centres could however be set up as logical extensions of the universities.

58. The number of men trained to a high academic level must be related to the provision of work in which their talents can be fully exercised.

REFERENCES

1. "World Reactor Chart" "Nuclear Power" January (1962).

2. "World Power Reactors, Built Building and Planned" "Nucleonics" August (1962).

3. S.A.Ghalib "Nuclear power in underdeveloped countries; financial considerations" Sixth World Power Conference, Melbourne, October (1962). Paper XII 2/10.

4. R.D. Vaughan, "The technical and economic development of the gas cooled reactor" World Power Conference Sectional Meeting, Madrid June (1960). Paper IV B/11.

5. "Training in radiological health and safety" (Veale Report) H.M.S.O. February (1960).

6. A.L. Shaw "Medium output gas cooled graphite moderated reactors for Australia" Australian Atomic Energy Symposium, Sydney (1958).

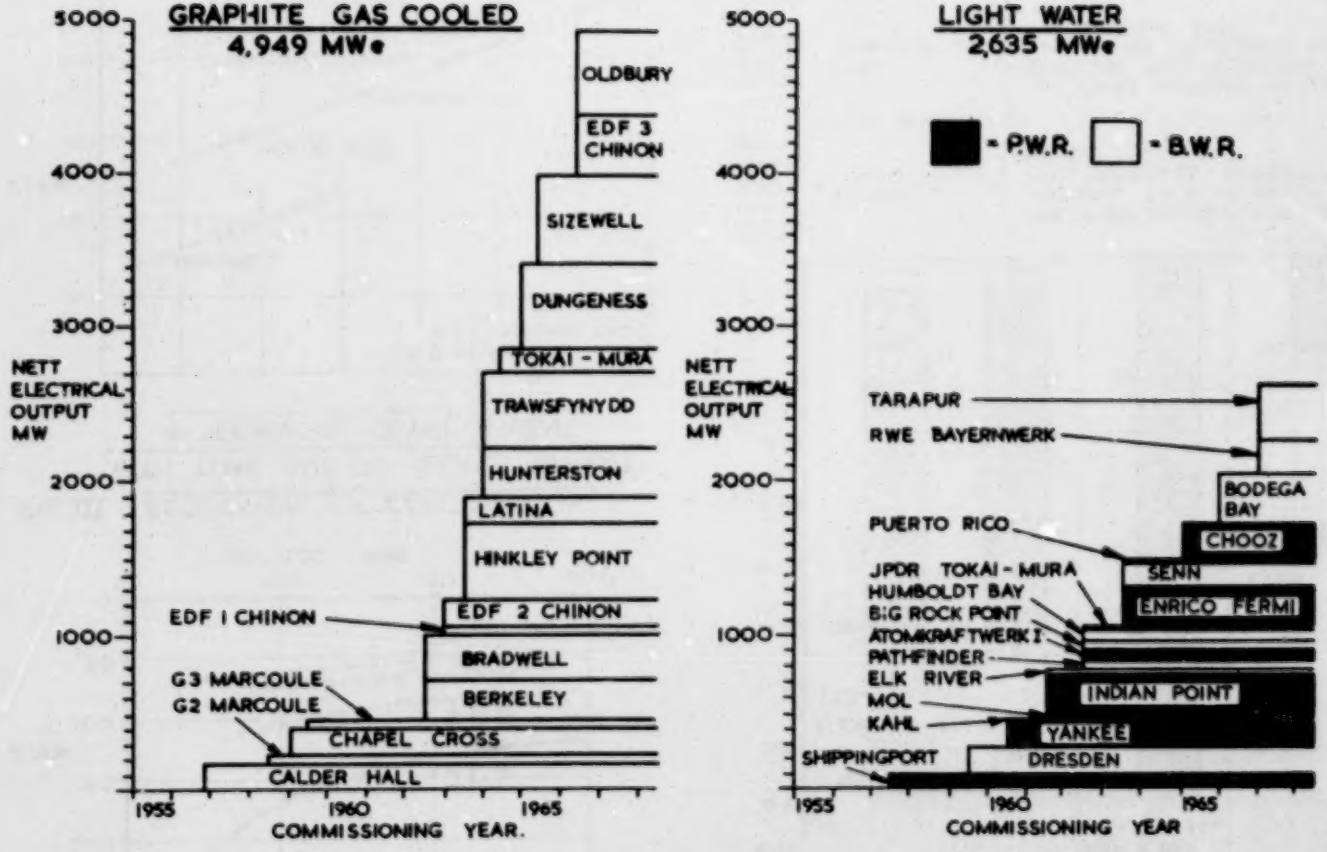


FIGURE I

NUCLEAR STATIONS OPERATING OR UNDER CONSTRUCTION.

FIG II SPECIFIC CAPITAL COST V UNIT SIZE FOR SINGLE REACTOR STATIONS.

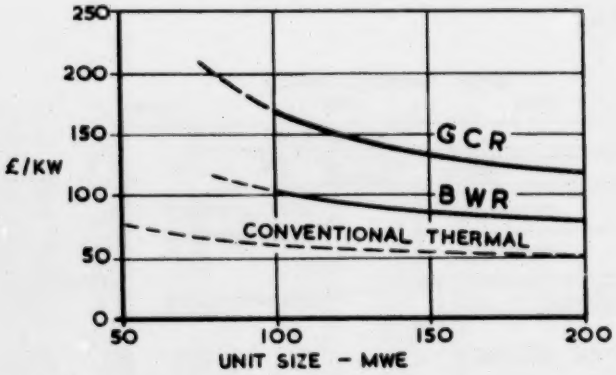


FIG III REDUCTION OF CAPITAL COST WITH TIME DUE TO SCALE EFFECT + TECHNICAL DEVELOPMENT

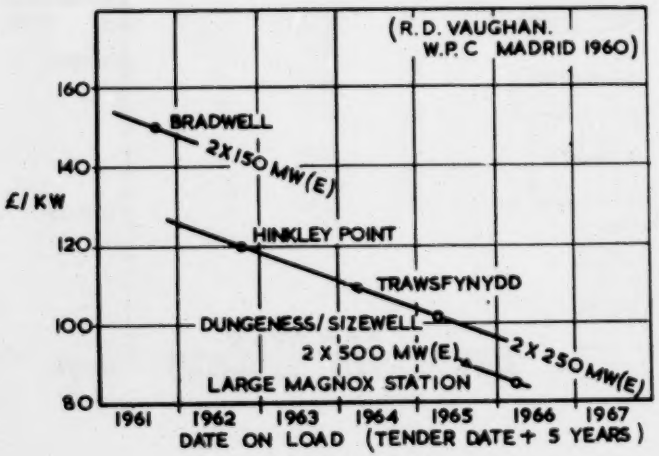
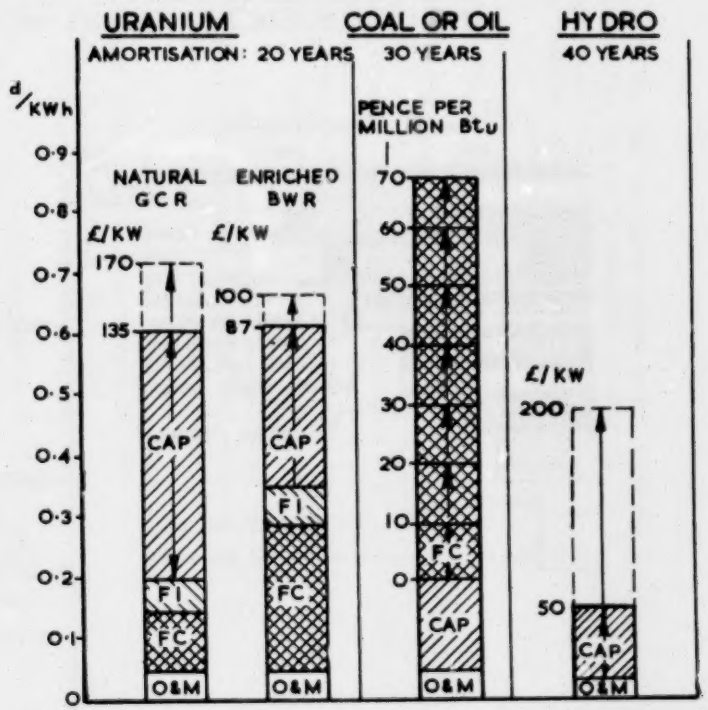


FIG IV TYPICAL GENERATION COST RANGES.

BASIS :- 5½% INTEREST 75% LOAD FACTOR



NOTES

CAP = CAPITAL CHARGES. — THE CHIEF VARIABLE FOR NUCLEAR AND HYDRO STATIONS, EACH OF WHICH IS SHOWN AT TWO EXTREMES EXPECTED IN 100-150 MWE RANGE

FI = FUEL INVESTMENT

FC = FUEL CONSUMPTION — THE CHIEF VARIABLE IN COAL OR OIL FIRED STATIONS, AND IS SHOWN FOR VARIOUS VALUES OF DELIVERED COST UP TO 70d PER MILLION Btu

O&M = OPERATION & MAINTENANCE — TAKEN ARBITRARILY AS 0·05d/KWh FOR NUCLEAR, COAL AND OIL AND 0·03d/KWh FOR HYDRO.

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